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Joe

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(54) **METHOD OF FORMING AN OXIDE LAYER**

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(58) **Field of Classification Search** 438/769–770, 438/773–774; 257/E21.284
See application file for complete search history.

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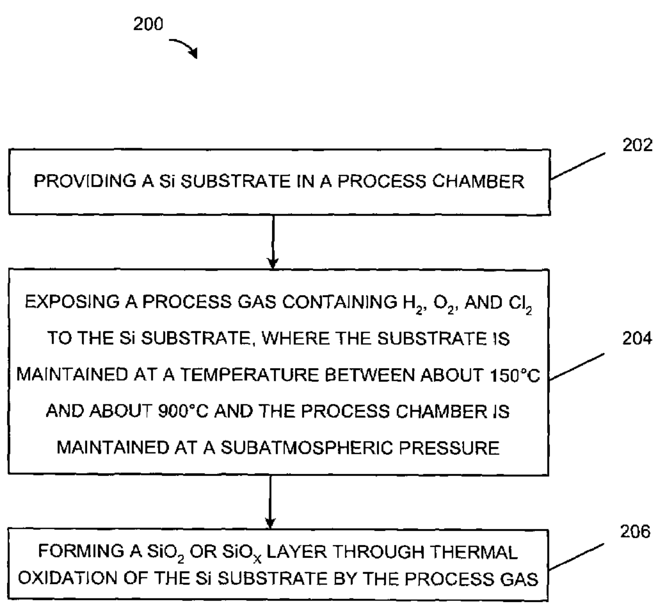
(57) **ABSTRACT**

A method for forming an oxide layer on a substrate. The method includes exposing a process gas containing H_2, an oxygen-containing gas, and a halogen-containing oxidation accelerant gas to the substrate, where the process chamber is maintained at a subatmospheric pressure, and forming an oxide layer through thermal oxidization of the substrate by the process gas. According to one embodiment of the invention, the substrate can be maintained at a temperature between about 150° C. and about 900° C. A microstructure containing an oxide layer is described, where the oxide layer can be a gate dielectric oxide layer or an interface oxide layer integrated with a high-k layer.

21 Claims, 5 Drawing Sheets



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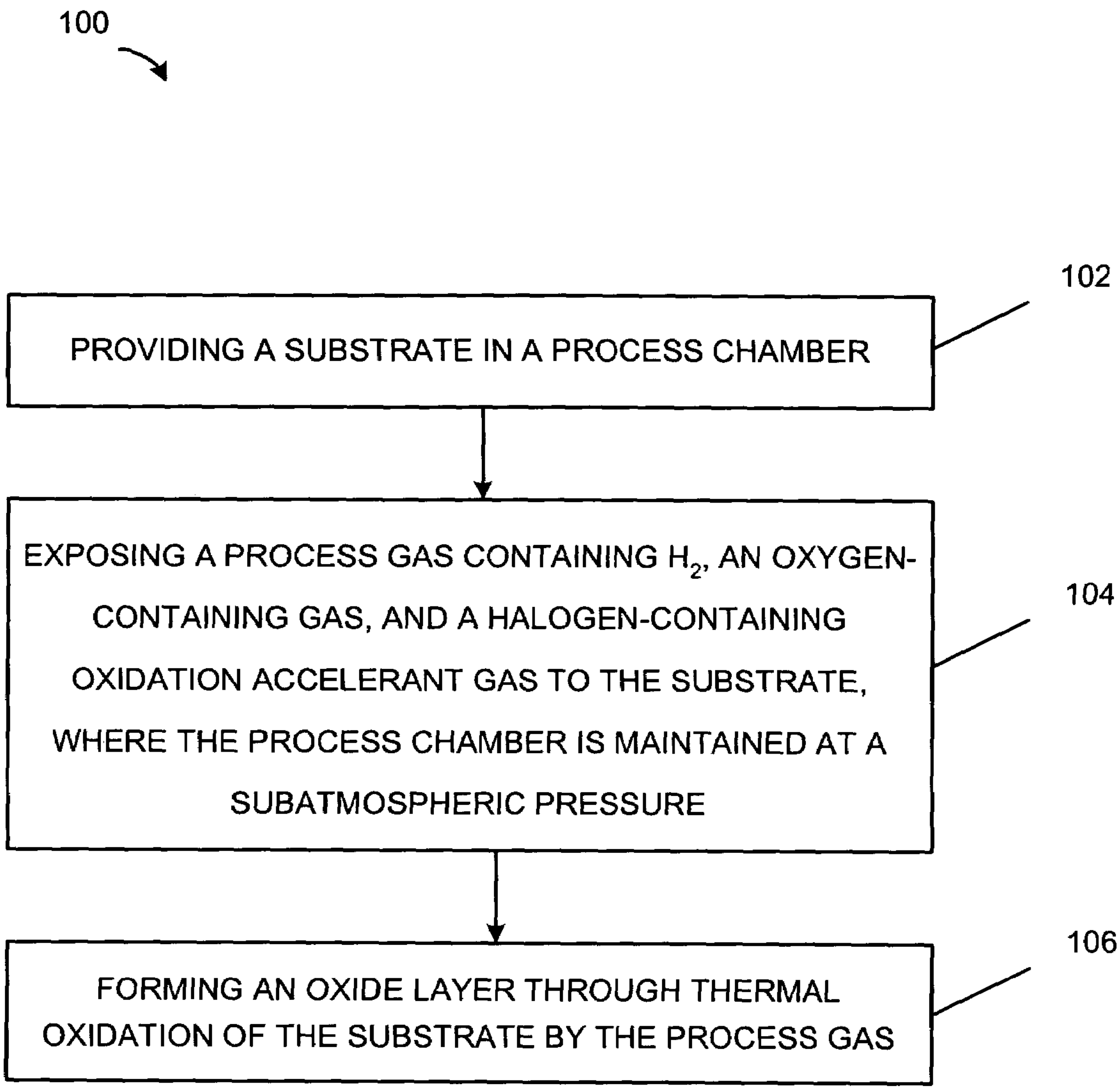
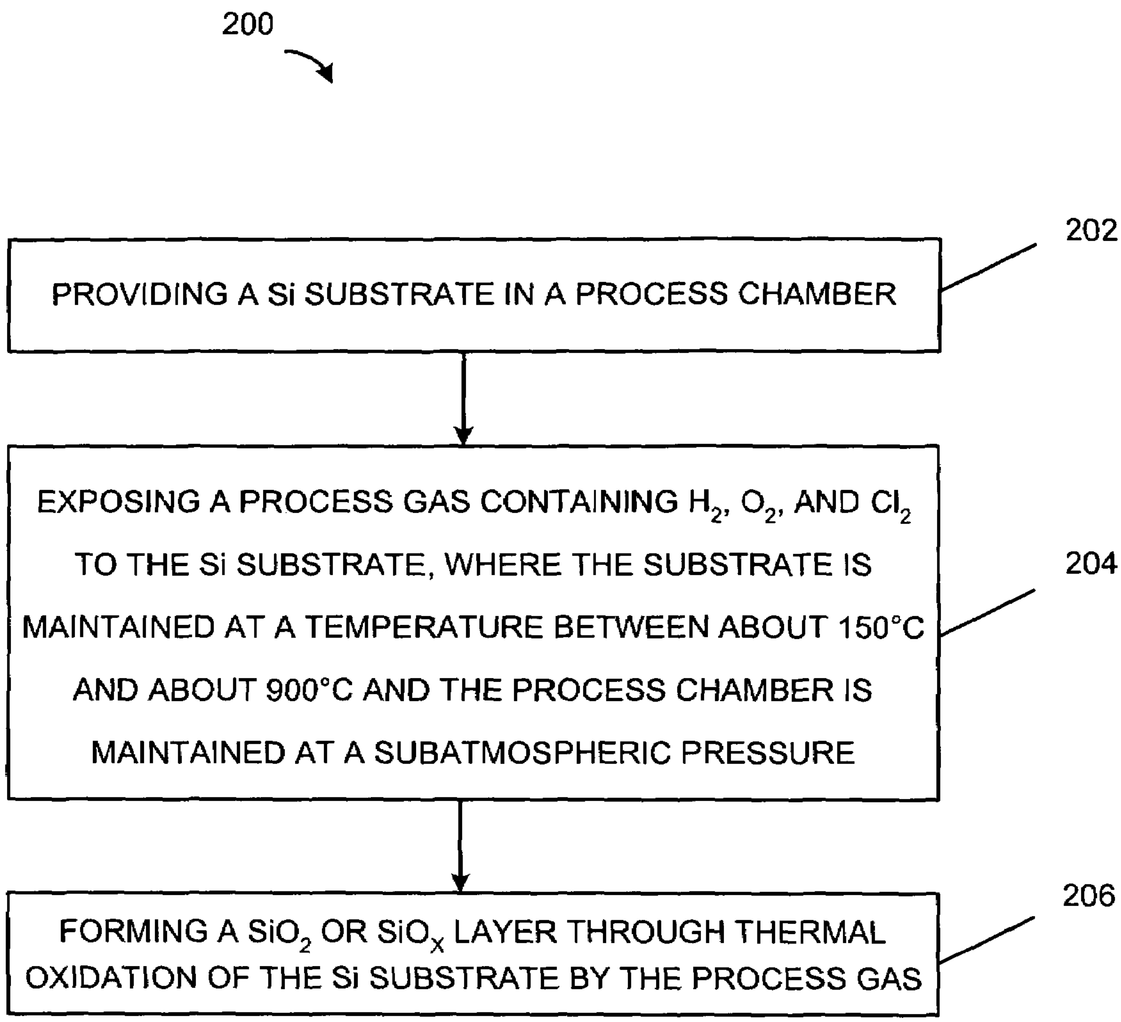

100
102
PROVIDING A SUBSTRATE IN A PROCESS CHAMBER
104
EXPOSING A PROCESS GAS CONTAINING H_2, AN OXYGEN-CONTAINING GAS, AND A HALOGEN-CONTAINING OXIDATION ACCELERANT GAS TO THE SUBSTRATE, WHERE THE PROCESS CHAMBER IS MAINTAINED AT A SUBATMOSPHERIC PRESSURE
106
FORMING AN OXIDE LAYER THROUGH THERMAL OXIDATION OF THE SUBSTRATE BY THE PROCESS GAS

FIG. 1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PROVIDING A Si SUBSTRATE IN A PROCESS CHAMBER
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EXPOSING A PROCESS GAS CONTAINING H_2, O_2, AND Cl_2 TO THE Si SUBSTRATE, WHERE THE SUBSTRATE IS MAINTAINED AT A TEMPERATURE BETWEEN ABOUT 150°C AND ABOUT 900°C AND THE PROCESS CHAMBER IS MAINTAINED AT A SUBATMOSPHERIC PRESSURE
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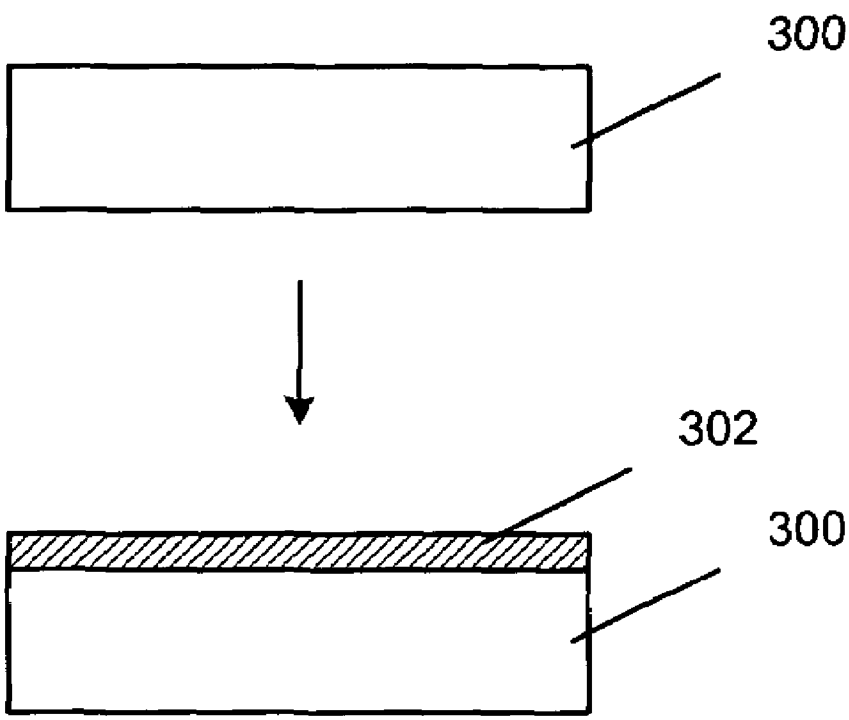
FORMING A SiO_2 OR SiO_X LAYER THROUGH THERMAL OXIDATION OF THE Si SUBSTRATE BY THE PROCESS GAS

FIG. 2

FIG. 3A

FIG. 3B



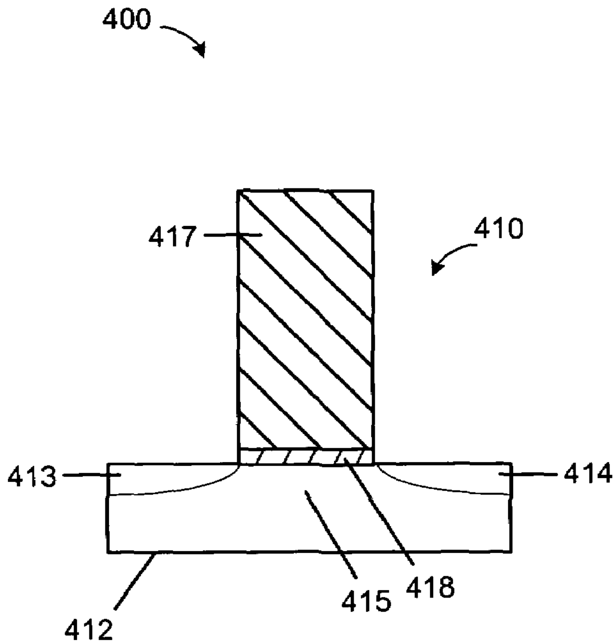

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FIG. 4A

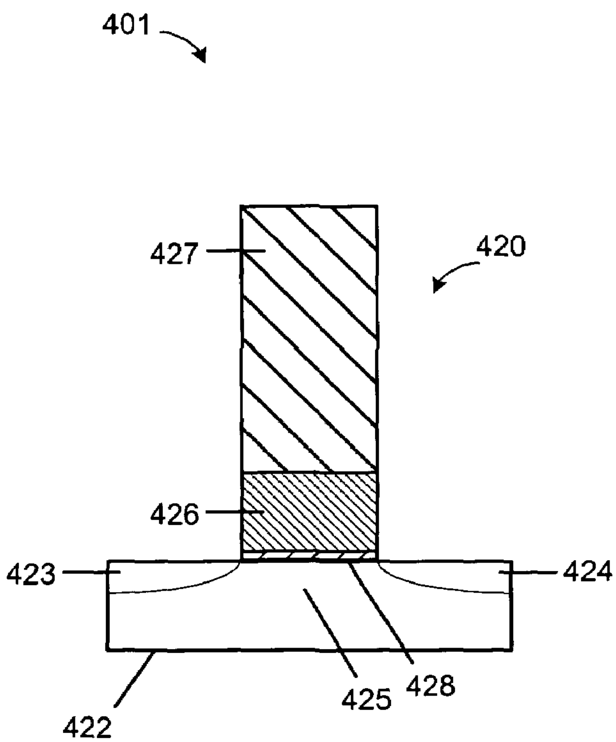
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FIG. 4B

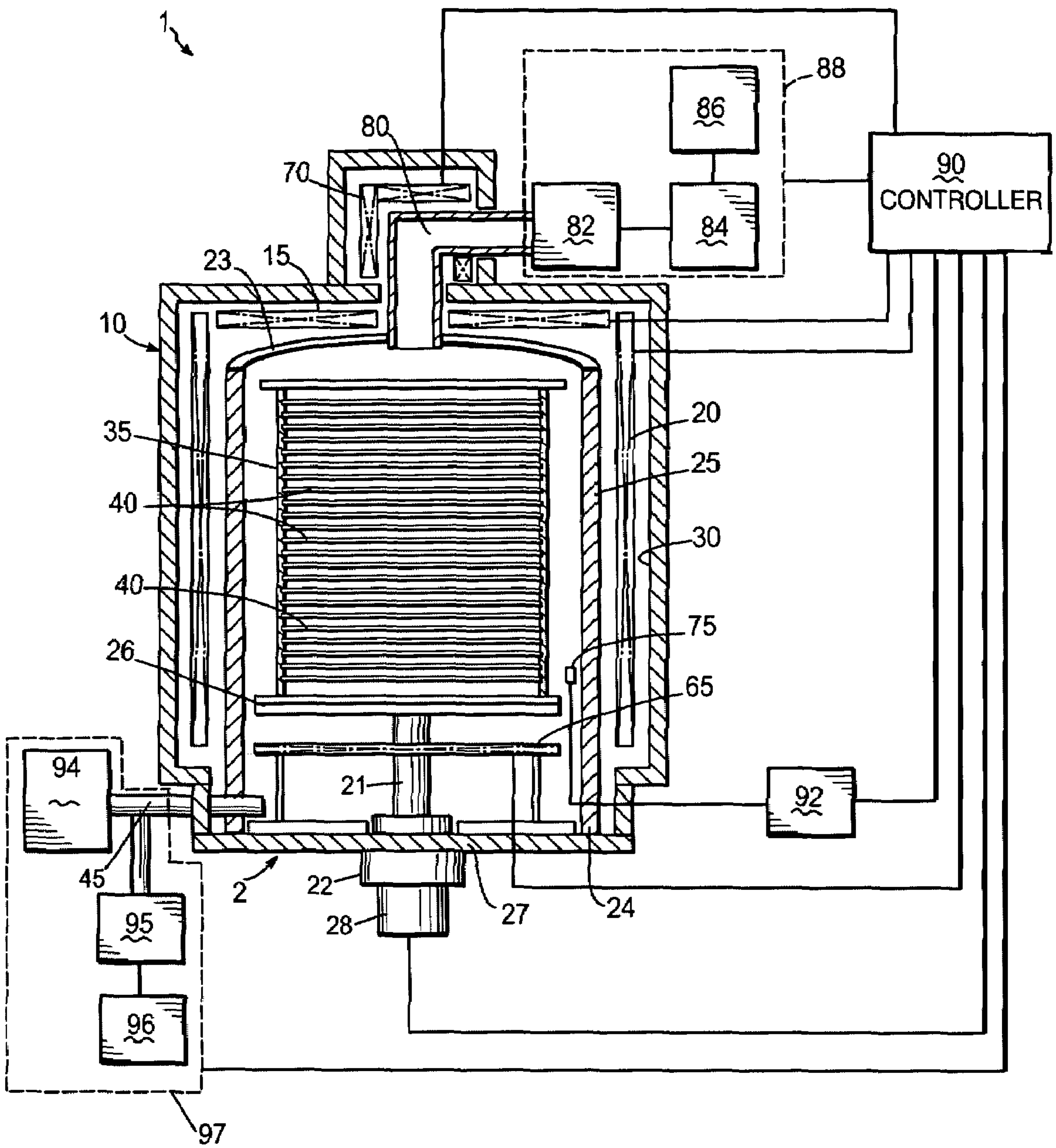
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FIG. 5

METHOD OF FORMING AN OXIDE LAYER

FIELD OF THE INVENTION

The present invention relates to semiconductor processing, and more particularly, to utilizing a halogen-containing oxidation accelerant gas to form an oxide layer through thermal oxidation of a substrate.

BACKGROUND OF THE INVENTION

Thin oxide layers are commonly used as dielectric layers at a surface of an integrated circuit. This is in part because of good electrical properties of the oxide layers, including high electron mobility and low electron trap densities.

Low pressure radical oxidation (LPRO) of substrates is a known method for reliably forming oxide layers with excellent electrical properties. Further, LPRO provides excellent non-selectivity of the oxide growth among planar and irregular substrate surfaces. However, LPRO requires high processing temperatures in order to provide practical oxidation rates for device manufacturing. As circuit geometries shrink to ever smaller feature sizes and new materials are introduced into semiconductor devices, the thermal budget of many manufacturing processes is reduced. Thus, despite its benefits, LPRO processes have not been utilized in the manufacturing of low feature size devices, or other processes requiring low thermal budget.

SUMMARY OF THE INVENTION

Accordingly, an object of the present invention is to address the above-described and/or other problems related to thermal oxide growth.

Another object of the present invention is to provide a low temperature oxidation process for forming an oxide with good electrical properties at a growth rate practical for device manufacturing.

Any of these and/or other objects can be provided by a method for forming an oxide layer through thermal oxidation of a substrate in accordance with the present invention. The oxide layer can, for example, be used as a gate dielectric oxide layer or as an interface oxide layer integrated with a high dielectric constant material.

In one embodiment of the invention, the method includes exposing H_2, an oxygen-containing gas, and a halogen-containing oxidation accelerant gas to the substrate, while the process chamber is maintained at a subatmospheric pressure. An oxide layer is then formed through thermal oxidization of the substrate by the process gas.

In another embodiment of the invention, the method includes providing a Si substrate in a process chamber, exposing a process gas comprising H_2, O_2, and a Cl_2 oxidation accelerant gas to the substrate, wherein the substrate is maintained at a temperature between about 150° C. and about 900° C. and the process gas pressure is maintained between about 100 mTorr and about 650 Torr during the exposing. An SiO_2 or SiO_x layer through thermal oxidization of the Si substrate by the process gas.

According to one embodiment of the invention, a microstructure is provided. The microstructure contains a substrate, a gate stack on the substrate, where the gate stack includes a gate electrode layer, and an gate dielectric oxide layer formed through thermal oxidation of the substrate by exposing the substrate to a process gas comprising H_2, an oxygen-containing gas, and a halogen-containing oxidation accelerant gas, where the process gas is maintained at a subatmospheric pressure during the exposing. According to another embodiment of the invention, the gate dielectric oxide layer can be an interface oxide layer integrated with a high-k layer.

BRIEF DESCRIPTION OF THE DRAWINGS

In the accompanying drawings:

FIG. **1** is a process flow diagram of a method of forming an oxide layer according to an embodiment of the invention;

FIG. **2** is a process flow diagram of a method of forming an oxide layer according to another embodiment of the invention;

FIGS. **3**A-**3**B schematically show a cross-sectional view of forming an oxide layer according to an embodiment of the invention;

FIG. **4**A schematically shows a cross-sectional view of a microstructure according to an embodiment of the invention;

FIG. **4**B schematically shows a cross-sectional view of another microstructure according to an embodiment of the invention; and

FIG. **5** shows a schematic view of a batch processing system for forming an oxide layer according to an embodiment of the invention.

DETAILED DESCRIPTION OF SEVERAL EMBODIMENTS OF THE INVENTION

As noted above, the benefits of LPRO grown oxides have gone largely unrealized in substrate processes requiring a low thermal budget, such as production of small featured devices. Specifically, a substrate temperature of about 900° C., or higher, may be required for a conventional LPRO process performed at subatmospheric pressures (e.g., below about 10 Torr) utilizing a process gas containing H_2 and O_2. For example, in the in-situ steam generation (ISSG) oxidation technique, H_2 and O_2 are directly introduced into a process chamber without pre-combustion. The combustion-like reactions between H_2 and O_2 occur at the substrate surface at over 900° C. to produce gas-phase radicals that readily react with and oxidize the substrate. Possible active oxidation species are OH radicals, O radicals, and atomic O. However, such temperatures during growth of an interface oxide or gate dielectric oxide can cause unwanted diffusion of previously formed impurity regions, for example.

Based on the above problem, the present inventors have studied the chemical interaction of oxygen containing gasses and hydrogen containing gasses during a thermal oxidation process at subatmospheric pressure. In particular, the present inventors studied the effect of introducing a halogen containing gas as a third reactant in the oxidation process. While halogens have been previously used in oxidation growth, they have been typically used at atmospheric pressure, or as part of an oxygen or hydrogen containing gas in a two reactant process.

Based on the above studies, the present inventors discovered that when interacting with a heated substrate, the halogen-containing gas can form halogen-containing radicals that can subsequently catalyze formation of oxidation species from H_2 and/or the oxygen-containing gas. The activation energy for radical formation from the halogen-containing oxidation accelerant gas being lower than for H_2 and/or the oxygen-containing gas, along with low activation energy for the subsequent reaction of the halogen-containing radical with H_2 and/or the oxygen-containing gas to form H and O radicals is thought to lower the overall activation energy of the oxidation process. Thus, the use of a halogen-containing gas in combination with H_2 and an oxygen-containing gas accelerates the oxidation process thereby allowing for oxidizing the substrate at low substrate temperatures

In one example, the process gas can contain H_2, O_2, and Cl_2 oxidation accelerant gas. Cl_2 can react on the heated substrate surface to form Cl radicals that further react with H_2 to form HCl and H radicals. The HCl and the H radicals may further react with O_2 to form additional oxidation species such as O radicals in the process gas. This effect can provide sufficient oxidation growth at subatmospheric pressure at a substrate temperature of about 150°-900° C. Furthermore, it is contemplated that the HCl and the Cl radicals may help trap and deactivate metal contaminant ions on the substrate surface that can be detrimental to the oxidation process. In addition, the in-situ formation of HCl from Cl radicals and H_2 can be utilized to improve oxidation selectivity of Si relative to SiN.

Thus, embodiments of the invention provide a method for efficient substrate oxidation for semiconductor device manufacturing. The method may be implemented into current semiconductor device manufacturing without significant hardware modifications. According to an embodiment of the invention, a halogen-containing oxidation accelerant gas is added to H_2 and an oxygen-containing gas to reduce the substrate temperature required to achieve an acceptable oxidation rate of the substrate. The presence of the halogen-containing oxidation accelerant gas in the process gas increases the oxidation rate of the substrate and thereby allows for forming a high quality oxide layer with good electrical properties at relatively low substrate temperature.

According to an embodiment of the invention, one or more substrates are provided in a process chamber, a process gas comprising H_2, an oxygen-containing gas, and a halogen-containing oxidation accelerant gas is exposed to the substrate, where the process gas is maintained at a subatmospheric pressure during the exposing, and an oxide layer is formed through thermal oxidization of the substrate by the process gas. According to one embodiment of the invention, the substrate may be maintained at a temperature between about 150° C. and about 900° C. during the exposing. Alternately, the substrate may be maintained at a temperature between about 400° C. and about 800° C. Still alternately, the substrate may be maintained at a temperature between about 600° C. and about 800° C. Yet alternately, the substrate may be maintained at a temperature between about 400° C. and about 600° C. However, temperatures above 900° C. may also be used, for example if oxidation rates higher than that of normal LPRO processes are needed.

These methods provide for forming an oxide layer through thermal oxidation of a substrate. The oxide layer may be utilized as a dielectric layer in semiconductor microstructures, for example, as a gate dielectric oxide layer in a gate stack or as an interface oxide layer positioned integrated with a high-k material. The oxide layer can be ultra thin, for example of the order of few angstrom (angstrom=10^{-10} m).

Referring now to the drawings, FIG. **1** is a process flow diagram for forming an oxide layer according to an embodiment of the invention. Reference is also made to FIGS. **3**A-**3**B that schematically show a cross-sectional view of forming an oxide layer according to an embodiment of the invention. In FIG. **1**, in step **102** of the process **100**, a substrate **300** is provided in a process chamber of a processing system. The substrate **300** can, for example, contain Si, Ge, SiGe, or GaAs, and can contain at least one active region. In one example, a Si substrate can be of n- or p-type, depending on the type of device being formed. The substrate (wafer) can be of any size, for example a 200 mm substrate, a 300 mm substrate, or an even larger substrate.

Although not shown in FIG. **3**A, the substrate **300** can be cleaned of a native oxide layer prior to growing an oxide layer on the substrate **300**. The substrate **300** can be cleaned, for example, by placing it in a liquid bath containing dilute hydrofluoric acid (HF) or, alternatively, exposing it to HF gas phase etching. The dilute HF liquid solution can be a H_2O:HF (e.g., 50:1) mixture. Following the HF cleaning process, the substrate **300** can be rinsed in de-ionized (D.I.) water prior to the oxidation process.

In step **104**, a process gas containing H_2, an oxygen-containing gas, and a halogen-containing oxidation accelerant gas is exposed to the substrate **300**, where the process gas is maintained at a subatmospheric pressure during the exposing. The process gas can further include an inert gas, including Ar, He, Ne, Kr, Xe, or N_2, or a combination of two or more thereof, but this is not required for embodiments of the invention. According to an embodiment of the invention, the oxygen-containing gas can contain O_2, O_3, NO, NO_2, or N_2O, or a combination of two or more thereof. Furthermore, the halogen-containing oxidation accelerant gas can contain X_2, C_xX_y, or $C_xX_yH_z$, or a combination thereof. The X_2 can, for example, contain F_2, Cl_2, Br_2, or I_2, or a combination of two or more thereof. The C_xX_y can, for example, contain C_5F_8, C_4F_6, C_4F_8, or CF_4, or a combination of two or more thereof. The $C_xX_yH_z$ can, for example, contain CHF_3, CH_2F_2, $CHCl_3$, or CH_2Cl_2, or a combination of two or more thereof. In general, the halogen-containing oxidation accelerant gas may be selected from gases having lower activation energies for decomposition than H_2 and/or the oxygen-containing gas.

According to one embodiment of the invention, the halogen-containing oxidation accelerant gas in step **104** can contain HX and the process gas can be maintained at a subatmospheric pressure greater than 1 Torr during the exposing. The HX can, for example, contain HF, HCl, HBr, or HI, or a combination of two or more thereof.

According to an embodiment of the invention, the volume percentages of one or more of the H_2, the oxygen-containing gas, and the halogen containing accelerant gas can be varied over wide concentration ranges while achieving acceptable oxidation rates of the substrate. Suitable relative concentrations of H_2, the oxygen-containing gas, and the halogen containing accelerant gas that enable growth of an oxide layer with a desired oxidation rate, thickness, thickness uniformity, and electrical properties, can be determined by direct experimentation and/or design of experiments (DOE).

According to one embodiment of the invention, the combined volume percentage of the H_2 and the halogen-containing oxidation accelerant gas in the process gas can be between about 1 percent and about 66 percent, and the volume percent of the oxygen-containing gas alone or with an inert gas can be between about 99 percent and about 34 percent. According to another embodiment of the invention, the combined volume percentage of the H_2 and the halogen-containing oxidation accelerant gas in the process gas can be between about 5 percent and about 30 percent, and the volume percent of the oxygen-containing gas alone or with an inert gas can be between about 95 percent and about 70 percent. According to yet another embodiment of the invention, the combined volume percentage of the H_2 and the halogen-containing oxidation accelerant gas in the process gas can be between about 10 percent and about 20 percent, and the volume percent of the oxygen-containing gas alone or with an inert gas is between about 90 percent and about

80 percent. These and other volume ratios may be implemented to achieve different oxide growth rates. For example, an increase volume percentage of H_2 will generally provide a reduced oxidation rate and less oxidation on a nitride substrate surface.

According to one embodiment of the invention, the volume percentage of the halogen-containing accelerant gas in the process gas can be between about 0.01 percent and about 65 percent. According to another embodiment of the invention, the volume percentage of the halogen-containing accelerant gas in the process gas can be between about 0.1 percent and about 10 percent. According to yet another embodiment of the invention, the volume percentage of the halogen-containing accelerant gas in the process gas can be between about 0.5 percent and about 5 percent. Other volume percentages of reactant gases may be implemented by one of ordinary skill in the art without departing from the scope of the present invention.

In step **106**, an oxide layer **302** is formed through thermal oxidation of the substrate **300** by the process gas. According to one embodiment of the invention, the substrate **300** can contain Si and the oxide layer **302** can contain SiO_2, or SiO_x where $x<2$. According to another embodiment of the invention, the substrate can contain Si_yGe_{1-y} and the oxide layer can contain $Si_yGe_{1-y}O_x$ where $0<y<1$ and $x\leqq 2$. According to yet another embodiment of the invention, the substrate **300** can contain Ge and the oxide layer **302** can contain GeO_2, or GeO_x where $x<2$. According to still another embodiment of the invention, the substrate **300** can contain GaAs and the oxide layer **302** can contain oxidized GaAs.

Suitable process conditions that enable growth of the oxide layer **302** to a desired thickness and thickness uniformity can be determined by direct experimentation and/or design of experiments. It is envisioned that oxide layers having thicknesses of about 5 angstrom to about 500 angstrom may be formed. For example, thin oxide layers with thicknesses less than about 30 angstrom may used as gate dielectric oxide layers. In another example, thick oxide layers with thicknesses between about 100 angstrom and about 500 angstrom may be used as gate oxide spacers and pad oxides. Thus, according to an embodiment of the invention, a thickness of the oxide layer **302** can be between about 5 angstrom and about 30 angstrom. Alternately, a thickness of the oxide layer **302** can be between about **100** angstrom and about 500 angstrom.

For example, adjustable process parameters can include exposure time, substrate temperature, process chamber pressure, and composition of the process gas. For example, in step **104**, the substrate **300** can be maintained at a temperature between about 150° C. and about 900° C. Other process parameters in step **104** include maintaining the process chamber at a pressure less than atmospheric pressure during the exposing. In one example, the process chamber can be maintained at a pressure between about 100 mTorr and about 650 Torr during the exposing. Alternately, the process chamber can be maintained at a pressure between about 200 mTorr and about 20 Torr during the exposing. Yet alternatively, the process chamber can be maintained at pressure between about 400 mTorr and about 10 Torr during the exposing. It is to be understood that process pressure may depend on the reactants used and/or process parameters.

FIG. **2** is a process flow diagram for forming an oxide layer according to another embodiment of the invention. In step **202** of the process **200**, a Si substrate is provided in a process chamber of a processing system. In step **204**, a process gas containing H_2, O_2, and a Cl_2 oxidation accelerant gas is exposed to the substrate, where the process chamber is maintained at subatmospheric pressure. In step **206**, a SiO_2 or SiO_x layer is formed through thermal oxidation of the Si substrate by the process gas. For example, in step **204**, the substrate can be maintained at a temperature between about 150° C. and about 900° C.

FIGS. **4**A and **4**B schematically shows cross-sectional views of microstructures according to embodiments of the invention. The microstructures contain oxide layers that may be formed according to embodiments of the invention. The oxide layers may utilized as dielectric layers in gate stacks, for example, as a gate dielectric oxide layer **418** depicted in FIG. **4**A, or as an oxide interface layer **428** integrated with a high-k material depicted in FIG. **4**B. Dielectric materials featuring a dielectric constant greater than that of SiO_2 (k~3.9) are commonly referred to as high-k materials. A high-k layer can, for example, contain a metal oxide, a metal oxynitride, a metal silicate, or a nitrated metal silicate, including Ta_2O_5, $TaSiO_x$, $TaSiO_xN_y$, TiO_2, ZrO_2, Al_2O_3, Y_2O_3, HfO_2, $HfSiO_x$, $HfSiO_xN_y$, HfO_xN_y, ZrO_2, $ZrSiO_x$, $ZrSiO_xN_y$, ZrO_xN_y, SrO_x, $SrSiO_x$, $SrSiO_xN_y$, LaO_x, $LaSiO_x$, $LaSiO_xN_y$, YO_x, $YSiO_x$, or $YSiO_xN_y$, or combination or mixture of two or more thereof.

In current semiconductor devices, one function of a dielectric layer in a gate stack is to "gate" the electrons, by controlling the flow of electricity across the transistor. With the introduction of high-k materials, these oxide layers will likely still be required at the channel and/or gate electrode to preserve interface state characteristics. This can include forming an interface oxide layer with good electrical properties, preventing uncontrolled Si surface oxidation, reducing reactions between different layers, and acting as a barrier layer to prevent diffusion of atoms to the different layers (e.g., dopant penetration from a gate electrode layer into the substrate). In practice, good device performance depends on controlling the thickness of the oxide layer, such that it remains thin, thereby avoiding increasing the equivalent oxide thickness (EOT) of the gate structure.

In FIG. **4**A, the microstructure **400** contains a gate stack **410** and a substrate **412** having a source region **413**, a drain region **414**, and a channel region **415**. The gate stack **410** contains a gate dielectric oxide layer **418** formed on the substrate **412**, and a gate electrode layer **417** formed on the gate dielectric oxide layer **418**. The gate dielectric oxide layer **418** can be formed through thermal oxidation of the substrate **412** by a process gas containing H_2, an oxygen-containing gas, and a halogen-containing oxidation accelerant gas as described in reference to FIGS. **1-3** above. The substrate **412** can, for example, contain Si, Ge, SiGe, or GaAs. According to one embodiment of the invention, the substrate **412** can contain Si and the gate dielectric oxide layer **418** can contain SiO_2 or SiO_x where $x<2$. According to another embodiment of the invention, the substrate can contain Si_yGe_{1-y} and the gate dielectric oxide layer **418** can contain $Si_yGe_{1-y}O_x$ where $0<y<1$ and $x\leqq 2$. According to yet another embodiment of the invention, the substrate **412** can contain Ge and the gate dielectric oxide layer **418** can contain GeO_2 or GeO_x where $x<2$. The thickness of the gate dielectric oxide layer **418** can, for example be between about 5 angstrom and about 30 angstrom, but this is not required for embodiments of the invention as the oxide layer **418** can have other thicknesses. Alternately, a thickness of the gate dielectric oxide layer **418** can be between about 7 angstrom and about 15 angstrom. The gate electrode layer **417** can, for example, be about 1000 angstrom thick. The gate electrode layer **417** can contain silicon (e.g., doped poly-Si), or a metal or metal-containing material, including W, WN, Al, Mo, Ta, TaN, TaSiN, HfN, HfSiN, Ti, TiN, TiSiN, Mo, MoN, Re, or Ru.

In FIG. 4B, the microstructure **401** contains a gate stack **420** and a substrate **422** having a source region **423**, a drain region **424**, and a channel region **425**. The gate stack **420** contains an oxide interface layer **428** formed on the substrate **422**, and a gate electrode layer **427** formed on the oxide interface layer **428**. The oxide interface layer **428** can be formed through thermal oxidation of the substrate **422** by a process gas containing H_2, an oxygen-containing gas, and a halogen-containing oxidation accelerant gas. As described in reference to substrate **412** in FIG. 4A, the substrate **422** in FIG. 4B can, for example, contain Si, Ge, or SiGe, or GaAs. The thickness of the oxide interface layer **428** can, for example be between about 5 angstrom and about 30 angstrom, but this is not required for embodiments of the invention as the oxide interface layer **428** can have other thicknesses. Alternately, a thickness of the oxide interface layer **428** can be between about 7 angstrom and about 15 angstrom. The oxide interface layer **428** can be thinner than the oxide interface layer **418** and the high-k layer **427** can be physically thicker than the oxide dielectric layer **418**, while attaining the necessary capacitance in the gate stack **420**. The high-k layer **426** can, for example, be between about 10 angstrom and about 200 angstrom thick. Alternately, the thickness of the high-k layer **426** can be between about 20 angstrom and about 50 angstrom.

FIG. **5** shows a simplified block diagram of a batch processing system for forming an oxide layer according to an embodiment of the invention. The batch processing system **1** contains a process chamber **10** and a process tube **25** that has an upper end **23** connected to an exhaust pipe **80**, and a lower end **24** hermetically joined to a lid **27** of cylindrical manifold **2**. The exhaust pipe **80** discharges gases from the process tube **25** to a vacuum pumping system **88** to maintain a pre-determined subatmospheric pressure in the processing system **1**. A substrate holder **35** for holding a plurality of substrates (wafers) **40** in a tier-like manner (in respective horizontal planes at vertical intervals) is placed in the process tube **25**. The substrate holder **35** resides on a turntable **26** that is mounted on a rotating shaft **21** penetrating the lid **27** and driven by a motor **28**. The turntable **26** can be rotated during processing to improve overall film uniformity or, alternately, the turntable can be stationary during processing. The lid **27** is mounted on an elevator **22** for transferring the substrate holder **35** in and out of the process tube **25**. When the lid **27** is positioned at its uppermost position, the lid **27** is adapted to close the open end of the manifold **2**.

A gas delivery system **97** is configured for introducing gases into the process chamber **10**. A plurality of gas supply lines can be arranged around the manifold **2** to supply a plurality of gases into the process tube **25** through the gas supply lines. In FIG. **5**, only one gas supply line **45** among the plurality of gas supply lines is shown. The gas supply line **45** shown, is connected to a first gas source **94**. In general, the first gas source **94** can supply gases for processing the substrates **40**, including H_2, an oxygen-containing gas, and an a halogen-containing oxidation accelerant gas for forming an oxide layer on the substrates **40**. Furthermore, the first gas source **94** can supply an inert gas. In addition, or in the alternate, one or more gases can be supplied from the (remote) plasma source **95** that is operatively coupled to a second gas source **96** and to the process chamber **10** by the gas supply line **45**. The plasma-excited gas is introduced into the process tube **25** by the gas supply line **45**. The plasma source **95** can, for example, be a microwave plasma source, a radio frequency (RF) plasma source, or a plasma source powered by light radiation. In the case of a microwave plasma source, the microwave power can be between about 500 Watts (W) and about 5,000 W. The microwave frequency can, for example, be 2.45 GHz or 8.3 GHz. In one example, the remote plasma source can be a Downstream Plasma Source Type AX7610, manufactured by MKS Instruments, Wilmington, Mass., USA.

A cylindrical heat reflector **30** is disposed so as to cover the reaction tube **25**. The heat reflector **30** has a mirror-finished inner surface to suppress dissipation of radiation heat radiated by main heater **20**, bottom heater **65**, top heater **15**, and exhaust pipe heater **70**. A helical cooling water passage (not shown) can be formed in the wall of the process chamber **10** as a cooling medium passage. The heaters **20**, **65**, and **15** can, for example, maintain the temperature of the substrates **40** between about 20° C. and about 900° C.

The vacuum pumping system **88** comprises a vacuum pump **86**, a trap **84**, and automatic pressure controller (APC) **82**. The vacuum pump **86** can, for example, include a dry vacuum pump capable of a pumping speed up to 20,000 liters per second (and greater). During processing, gases can be introduced into the process chamber **10** via the gas supply line **45** of the gas delivery system **97** and the process pressure can be adjusted by the APC **82**. The trap **84** can collect unreacted precursor material and by-products from the process chamber **10**.

The process monitoring system **92** comprises a sensor **75** capable of real-time process monitoring and can, for example, include a mass spectrometer (MS), a FTIR spectrometer, or a particle counter. A controller **90** includes a microprocessor, a memory, and a digital I/O port capable of generating control voltages sufficient to communicate and activate inputs to the processing system **1** as well as monitor outputs from the processing system **1**. Moreover, the controller **90** is coupled to and can exchange information with gas delivery system **97**, motor **28**, process monitoring system **92**, heaters **20**, **15**, **65**, and **70**, and vacuum pumping system **88**. The controller **90** may be implemented as a DELL PRECISION WORKSTATION 610™. The controller **90** may also be implemented as a general purpose computer, processor, digital signal processor, etc., which causes a substrate processing apparatus to perform a portion or all of the processing steps of the invention in response to the controller **90** executing one or more sequences of one or more instructions contained in a computer readable medium. The computer readable medium or memory for holding instructions programmed according to the teachings of the invention and for containing data structures, tables, records, or other data described herein. Examples of computer readable media are compact discs, hard disks, floppy disks, tape, magneto-optical disks, PROMs (EPROM, EEPROM, flash EPROM), DRAM, SRAM, SDRAM, or any other magnetic medium, compact discs (e.g., CD-ROM), or any other optical medium, punch cards, paper tape, or other physical medium with patterns of holes, a carrier wave (described below), or any other medium from which a computer can read.

The controller **90** may be locally located relative to the processing system **1**, or it may be remotely located relative to the processing system **1** via an internet or intranet. Thus, the controller **90** can exchange data with the processing system **1** using at least one of a direct connection, an intranet, and the internet. The controller **90** may be coupled to an intranet at a customer site (i.e., a device maker, etc.), or coupled to an intranet at a vendor site (i.e., an equipment manufacturer). Furthermore, another computer (i.e., controller, server, etc.) can access controller **90** to exchange data via at least one of a direct connection, an intranet, and the internet.

It is to be understood that the batch processing system **1** depicted in FIG. **5** is shown for exemplary purposes only, as many variations of the specific hardware can be used to practice embodiments of the invention, and these variations will be readily apparent to one having ordinary skill in the art. The processing system **1** in FIG. **5** can, for example, process substrates of any size, such as 200 mm substrates, 300 mm substrates, or even larger substrates. Furthermore, the processing system **1** can simultaneously process up to about 200 substrates, or more. Alternately, the processing system **1** can simultaneously process up to about 25 substrates.

Alternately, a single wafer deposition system may be used to form an oxide layer according to embodiments of the invention. One example of a single wafer deposition system is described in U.S. patent application Ser. No. 11/711,721, titled "A METHOD FOR FORMING A THIN COMPLETE HIGH-PERMITTIVITY DIELECTRIC LAYER", filed on Sep. 30, 2004, the entire contents of which are hereby incorporated by reference.

It should be understood that various modifications and variations of the present invention may be employed in practicing the invention. It is therefore to be understood that, within the scope of the appended claims, the invention may be practiced otherwise than as specifically described herein.

What is claimed is:

1. A method for processing a substrate, the method comprising:

providing the substrate in a process chamber;

maintaining the substrate at a temperature between about 150° C. and about 900° C.;

maintaining the process chamber at a pressure between about 100 mTorr and about 20 Torr;

exposing a process gas comprising H_2, an oxygen-containing gas, and a halogen-containing oxidation accelerant gas to the substrate, wherein the process chamber is maintained at said temperature and said pressure during the exposing; and

forming an oxide layer through thermal oxidization of the substrate by the process gas.

2. The method according to claim **1**, wherein the halogen-containing oxidation accelerant gas comprises X_2, C_xX_y, or $C_xX_yH_z$, or a combination of two or more thereof.

3. The method according to claim **2**, wherein the substrate is maintained at a temperature between about 400° C. about 800° C. during the exposing.

4. The method according to claim **2**, wherein the process chamber is maintained at a pressure between about 200 mTorr and about 20 Torr during the exposing.

5. The method according to claim **2**, wherein the process chamber is maintained at a pressure between about 400 mTorr and about 10 Torr during the exposing.

6. The method according to claim **2**, wherein the oxygen-containing gas comprises O_2, O_3, NO, NO_2, or N_2O, or a combination of two or more thereof.

7. The method according to claim **2**, wherein the X_2 comprises F_2, Cl_2, Br_2, or I_2, or a combination of two or more thereof.

8. The method according to claim **2**, wherein the C_xX_y comprises C_5F_8, C_4F_6, C_4F_8, or CF_4, or a combination of two or more thereof, and the $C_xH_yX_z$ comprises CHF_3, CH_2F_2, $CHCl_3$, or CH_2Cl_2, or a combination of two or more thereof.

9. The method according to claim **2**, wherein the process gas further comprises Ar, He, Ne, Kr, Xe, or N_2, or a combination of two or more thereof.

10. The method according to claim **2**, wherein the substrate comprises Si and the oxide layer comprises SiO_2 or SiO_x where x<2.

11. The method according to claim **2**, wherein the substrate comprises Ge and the oxide layer comprises GeO_2 or GeO_x where x<2.

12. The method according to claim **2**, wherein the substrate comprises Si_yGe_{1-y} and the oxide layer comprises $Si_yGe_{1-y}O_x$ with 0<y<1 and x≦2.

13. The method according to claim **2**, wherein the substrate comprises GaAs and the oxide layer comprises oxidized GaAs.

14. The method according to claim **2**, wherein a thickness of the oxide layer is between about 5 angstrom and about 500 angstrom.

15. The method according to claim **2**, wherein a thickness of the oxide layer is between about 5 angstrom and about 30 angstrom.

16. The method according to claim **2**, wherein a thickness of the oxide layer is between about 100 angstrom and about 500 angstrom.

17. The method according to claim **2**, wherein the combined volume percentage of the H_2 and the halogen-containing oxidation accelerant gas in the process gas is between about 1 percent and about 66 percent, and wherein the combined volume percentage of the oxygen-containing gas and optionally an inert gas is between about 99 percent and about 34 percent.

18. The method according to claim **2**, wherein the volume percentage of the halogen-containing accelerant gas in the process gas is between about 0.01 percent and about 65 percent.

19. The method of claim **1**, wherein said providing comprises providing a si substrate having at least one diffusion region therein, said exposing and forming being performed on the substrate having at least one diffusion region.

20. A method for processing a Si substrate, the method comprising:

providing the Si substrate in a process chamber;

exposing a process gas comprising H_2, O_2, and a Cl_2 oxidation accelerant gas to the Si substrate, wherein the Si substrate is maintained at a temperature between about 150° C. and about 900° C. and the process chamber is maintained at a subatmospheric pressure between about 100 mTorr and 20 Torr during the exposing; and

forming an SiO_2 or SiO_x layer through thermal oxidization of the Si substrate by the process gas.

21. The method of claim **20**, wherein said providing comprises providing a Si substrate having at least one diffusion region therein, said exposing and forming being performed on the Si substrate having at least one diffusion region.

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